Holographic Manipulation of a Cold Atomic Beam

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A method of generating an arbitrary pattern of atoms by using an interferometric technique is reported. A laser-cooled metastable Ne atomic beam in the $1s_3$ state is diffracted by a computer generated binary hologram. A black-and-white pattern is drawn on a microchannel detector with a spatial resolution exceeding 65 μm and a resolving power better than 30. [S0031-9007(96)00758-2]

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Holography is a technique in optics for converting an optical wave front interferometrically by transmitting through a hologram [1,2]. The hologram is fabricated either by photographic imaging of the interference pattern between the object and reference waves or by computer calculation of the interference pattern. The latter method is a technique for generating a wave front with an arbitrary shape from a simpler wave front. The same technique can in principle be used to generate an arbitrary pattern of an atomic de Broglie wave. However, the technical difficulty is much higher than in optical holography. First, the number-flux intensity of an atomic beam is many orders of magnitude smaller than that of an optical beam. The short wavelength of atomic waves is another obstacle. In addition, atoms cannot penetrate through a solid material, so the hologram for atoms must be composed of a film with real holes with submicrometer structure. Recent reports on the diffraction of atoms by a grating [3] or a Fresnel zone plate [4] may be interpreted as simple examples of holographic manipulation of atomic waves. We have demonstrated the manipulation of a laser-cooled Ne atomic beam in the $1s_3$ metastable state by a computer-generated Fourier hologram [5,6]. We report in this Letter the more general technique that enables us to draw an arbitrary pattern of atoms on a two-dimensional surface.

The position of through holes on the atomic hologram can be determined by a method similar to that used to generate a binary hologram in optics [7,8]. It consists of two steps. The first step is to calculate the transmission function of the hologram that diffracts a reference wave and generates the intended wave front. The second step is to approximate the transmission function by a binary pattern. We consider the case of generating an atomic wave front $F(X,Y)$ at some distance from a point source. In optics the wave front $F(X,Y)$ can be constructed with a Fourier hologram sandwiched between two lenses, where the first lens converts the diverging wave from the source to a parallel beam, and the second lens focuses the beam to a point at the distance we intend to make the wave front $F(X,Y)$. The transmission characteristics $f(x,y)$ of the hologram is the Fourier transform of the pattern, which is given by

$$f(x,y) = \frac{A}{L_2^2} \int \exp\left(ik\frac{xX + yY}{L_2}\right) F(X,Y)\, dX\, dY \,,$$

where A is a complex constant, k the wave vector, and L_2 is the focal length of the second lens. Since the Fourier transform of a function can be efficiently calculated by using the fast-Fourier-transform (FFT) algorithm, even a relatively complex interference pattern is easily calculated.

For a neutral atomic beam it is rather difficult to construct a convex lens. Therefore it is desirable to incorporate the function of the lenses into the hologram. This can be done without compromising the efficiency of the FFT calculation, provided that the divergence angle of the wave is not large, and therefore the paraxial approximation is valid. The hologram with the function of the lenses must have the transmission characteristics

$$f(x,y) = \frac{A}{L_2^2} \exp\left(-ik\frac{x^2 + y^2}{2L}\right) \int \exp\left(ik\frac{xX + yY}{L_2}\right) \times \left\{\exp\left(-ik\frac{X^2 + Y^2}{2L_2}\right) F(X,Y)\right\} dX\, dY \,, \quad (2)$$

with $L = (1/L_1 + 1/L_2)^{-1}$, where L_1 is the distance from the source to the hologram, and L_2 is the distance from the hologram to the image plane.

In the experiment we describe here, the acceleration of atoms by gravity is not negligible, and the atomic velocity changes along the atomic path. It is easily shown that Eq. (1) holds also in this case if we put $k = mv/\hbar$, $L_1 = vt_1$, and $L_2 = vt_2$, where v is the velocity at the hologram and t_1 and t_2 are the transit time from the source to the hologram and from the hologram to the image plane, respectively. Assuming that the velocity of atoms is zero at the source, the distances from the hologram to the source l_1 and from the hologram to the image plane l_2 are

$$l_1 = L_1/2$$

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and

$$l_2 = L_2(2L_1 + L_2)/2L_1 ,$$

respectively.

The acceleration due to gravity helps to improve the resolution of the image. At the hologram the velocity spread of atoms at the source Δv is compressed to $\Delta v^2/2v_h$, where v_h is the average atomic velocity at the hologram.

To achieve the transmission function $f(x,y)$ of Eq. (1) on a holographic film, $f(x,y)$ must be replaced with a real positive function $f_+(x,y)$. The standard method is to add the complex conjugate $f^\dagger(x,y)$ and a constant:

$$f_+(x,y) = f(x,y) + f^\dagger(x,y) + f_0. \tag{2}$$

The two added terms generate additional waves. The amplitude diffracted from the hologram is the sum of the wave that generates the intended pattern (the 1st order wave), the conjugate wave (-1th order wave) and the nondiffracted wave (0th order wave).

The final step is to approximate the transmission function $f_+(x,y)$ in Eq. (2) by a binary function. We used a (1024×1024)-point two-dimensional FFT to calculate $f_+(x,y)$. We added a random number on each calculated point of $f_+(x,y)$ and set a threshold f_{th} to decide whether the transmission of that point is either 0 or 1. For an optical hologram the ratio of the transparent to opaque areas is arbitrary. For an atomic hologram the transparent part consists of real holes. The entire opaque area must be connected and remain as a single piece. We chose the random numbers that were distributed uniformly between the maximum value $f_{\max}$ of $f_+(x,y)$ and 0. We set the constant f_0 to 0 and the threshold to $f_{\max}$.

Although the above procedure could in principle produce any complex wave front $F(X,Y)$, we considered only the intensity pattern $|F(X,Y)|^2$. This gave us additional freedom to assign arbitrary phase to the amplitude $F(X,Y)$. We multiplied the binary-valued amplitude function showing a black-and-white pattern by a random phase factor. This procedure reduced the intensity of the nondiffracted wave and maximized the contrast of the reconstructed pattern. Since the randomization of phase disperses the contribution of the integral Eq. (1) over a large area of the hologram, it also stabilized the pattern against a local defect of the hologram.

The hologram used in this experiment consisted of 1024×1024 cells 500 nm square and the total area was 0.5 mm square. It was designed to have a focal length of 241 mm for atoms with a de Broglie wavelength of 7.1 nm. It was made of a silicon nitride membrane 100 nm thick. The binary pattern was written by an electron beam on ZEP resist (a positive resist for electron beams from Nippon Zeon Co.) followed by CF_4 plasma etching. Scanning electron microscope (SEM) image of a part of the hologram that forms the pattern "NEC" and the theoretical pattern on the image plane are shown in Figs. 1(a) and 1(b), respectively. The square in the middle was formed by the nondiffracted wave. The conjugate wave had a virtual image between the source and the hologram. Therefore, the image was completely out of focus at the detector position and did not appear clearly in the figure. The portion of the transparent area on the hologram was approximately 8%.

The experimental setup was similar to that of our previous work on atom interferometry [9] and is shown in Fig. 2. The atomic source was metastable neon atoms in the $1s_3$ state that were released from the trap of $1s_5$ neon atoms by optical pumping using a 598 nm laser focused into the trap. The source size was approximately 100 μm. The velocity spread of atoms in the source was $\Delta v \approx 20$ cm/s. The atoms fell nearly vertically pulled by gravity. The hologram and a microchannel-plate detector (MCP) were placed vertically. The image of individual atoms that hit the MCP was recorded by a video recorder. Their position and intensity were retrieved from the video tape by using a video processor, and the atomic pattern on the detector was reconstructed.

Figure 3 shows the reconstructed atomic pattern, when $l_1 = 400$ mm and $l_2 = 420$ mm. The average velocity at the hologram v_h was 2.8 m/s corresponding to a de Broglie wavelength of 7.1 nm. The relative velocity spread $\Delta v_h/v_h$ was 3×10^{-3}. The data were

(a)
(b)

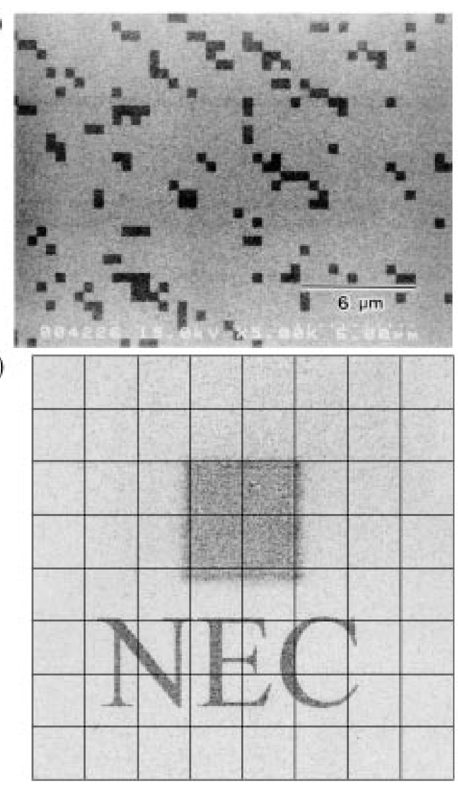

FIG. 1. (a) SEM photograph of a part of the hologram and (b) the calculated pattern of the reconstructed image. The total area of the hologram is 0.5×0.5 mm.

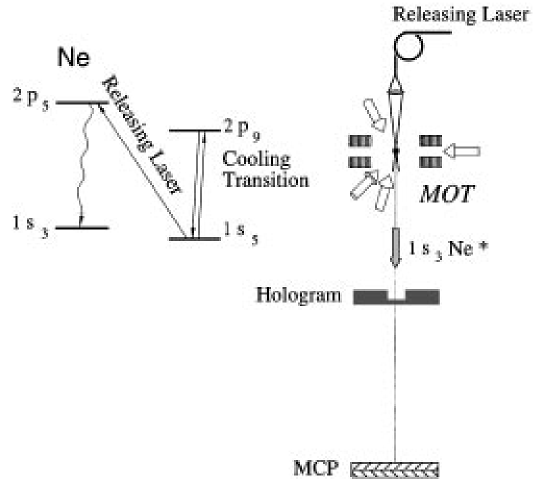

FIG. 2. Experimental setup of the holographic pattern generation.

accumulated for 2 h, and the total number of points in the figure was approximately 2.0×10^5. The points were produced almost entirely from one of the three waves diffracted from the hologram. The vacuum ultraviolet photons that were emitted by atoms in the trap when they decayed to the ground state were the largest source of noise points that constituted approximately 3% of the total count. The number of atoms that formed the letters "NEC" was 5.2×10^4, and the intensity ratio between the white and black area was approximately 7:1. The size of the square pattern from the nondiffracted wave was 0.7×0.7 mm. The spatial resolution of the pattern was estimated from the sharpness of the edge of the letter. Figure 4 shows the intensity profile measured along the three letters as indicated in the figure. The resolution in terms of 10 to 90% rise was 65μm, and the resolving

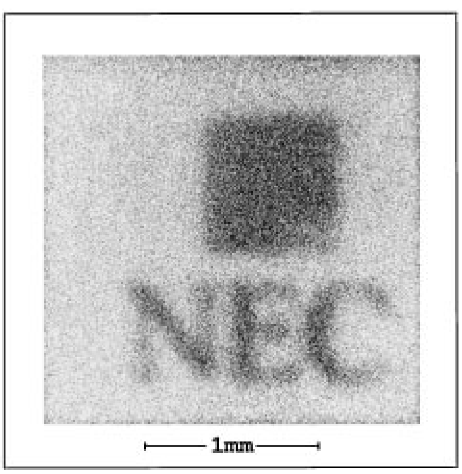

FIG. 3. Reconstructed pattern. The central square is the pattern of the 0th order wave. The pattern of the conjugate wave (-1th order wave) that covers the upper half of the figure is not clearly seen.

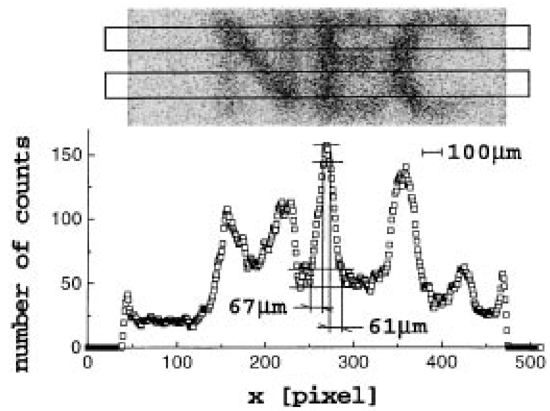

FIG. 4. Intensity profile of the reconstructed image along the three letters "NEC." The intensity was averaged along the vertical direction inside the two boxes shown at the top of the figure.

power (the ratio between the length of the figure and the resolution) was better than 30. This resulted from the finite size of the atomic source and the spatial resolution of the detector.

In conclusion, we have demonstrated for the first time the most general pattern generation of neutral atoms by a holographic technique. In view of the fact that manipulation of neutral atoms with electromagnetic lenses is rather difficult, the holographic method opens up new possibilities in various technical and scientific applications. The quality of the hologram may be evaluated by two quantities: resolution and resolving power. The resolving power P is limited by the number of holes N on the hologram along one direction. Another factor is the relative velocity spread $v/\delta v$. The number of holes is limited by the capacity of the computer and electron beam machine to etch the hologram. The velocity spread is limited by the atomic temperature in the source and the maximum gravity acceleration. The practical maximum value is in the order of 10^4. The resolution is affected by, in addition to the above quantities, the de Broglie wavelength and the size of the source and aperture of the hologram [10]. The spatial resolution obtained in this experiment is still 2 to 3 orders of magnitude worse than that achieved in the focusing of atoms with a standing light wave [11–13]. The ultimate resolution of the holographic manipulation is limited only by the de Broglie wavelength of the atom. When the hologram is the only component used to manipulate atoms, however, the practical resolution is approximately the size of the unit open hole of the hologram. This is understood by considering that a single hole can carry only a single information on the pattern of the reconstructed image, and that the waves diffracted from N holes have to overlap each other to obtain the resolving power of N. The present electron-beam etching technique can draw a structure on the film as small as 10 nm. Therefore, manipulation of atoms with resolution at least one order of magnitude smaller than the optical wavelength is possible.

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